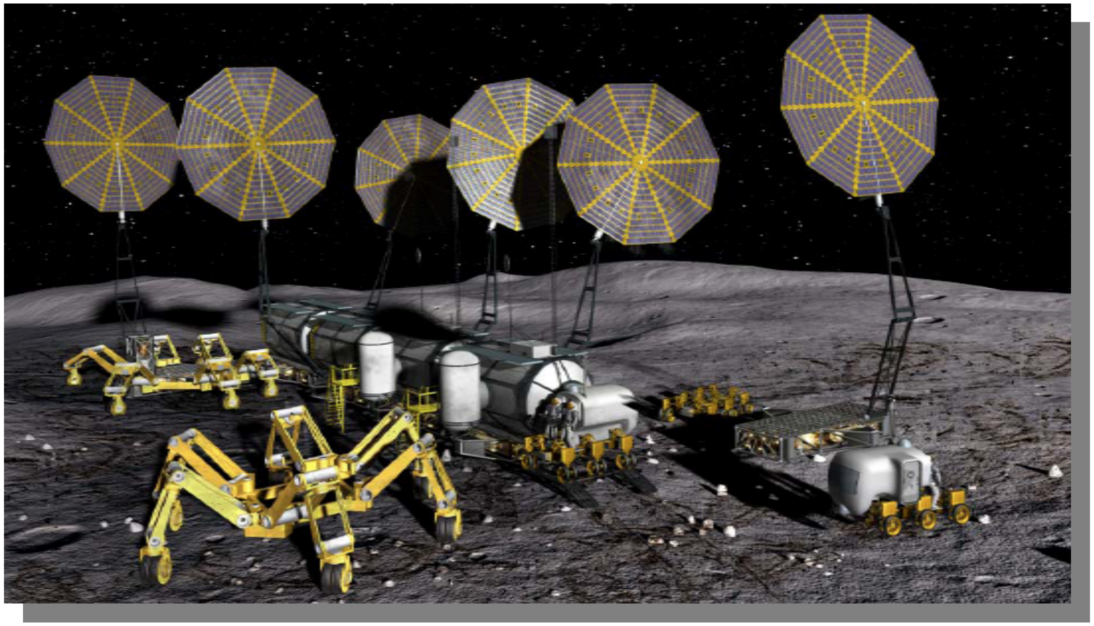
Lunar Architecture Analysis



Ed Crawley

Massachusetts Institute of Technology

February 25th, 2009

Thanks to: Bruce Cameron, Theo Seher, Bill Simmons, Arthur Guest, Wilfried Hofstetter , Ryan Boas

Motivation for a Great Architecture

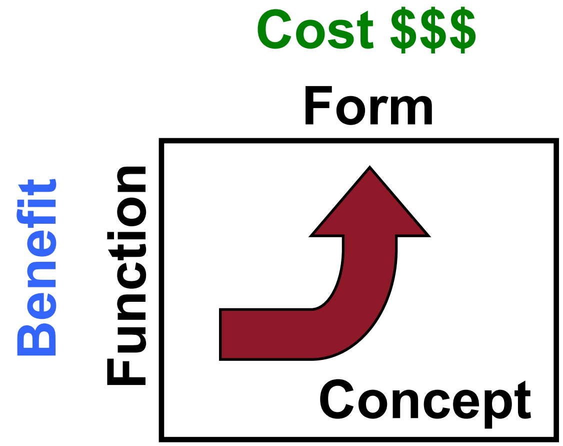
- Architecture is design at the system level
- We have before us the design of an *unprecedented* system to explore the solar system
- The system must meet the differing and changing needs of many stakeholders
- The system must be flexible, easily integrated, and have life-cycle affordability
- This is what sustainable and well architected systems do!

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

System Architecture

- Architecture
  - The allocation of physical/informational function to elements of form, and definition of relationships* among the elements.

- Consists of:
  - Function
  - Related by Concept
  - To Form



- Establishes value equation

** often, but not always defined by interfaces*

Why is System Architecture Important?

- Primary link between benefit and cost!
- High leverage on an organization's activities
  - Selection consumes a relatively small portion of an organization's efforts, yet decision dictates majority of work.
- Architecting can provide:
  - Cross project commonality and extensibility
  - Good interface control
  - Creative new solutions
- Source of sustainable competitive advantage
- Alignment with our role in development - architecting is what all our organizations do, and some do exclusively!

Outline: Three Principles of Architecting

- Focus on the Delivery of Value
- Comprehensively Search the Architecture Space to find Good Designs
- Adopt an Affordable Approach: Minimalist, Commonality, and Extensibility

Principle 1: Focus on the Delivery of Value

(7123.1, section 3.2.1 and 3.2.2.)

Architecting to Deliver Value

- A sustainable exploration enterprise must deliver value to its key stakeholders - this is why the nation invests!
- The flow of value in the exploration system is very complex, and should be:
  - Understood and carefully modeled
  - Considered critical and used in setting program goals
- A method of closed loop stakeholder value network analysis has been developed, which gives insight into NASA's opportunities to create stakeholder value
- The analysis shows that the greatest value delivery comes in campaign design, and in a few specific aspects of the system design, but not in the transportation systems and surface infrastructure

Exploration Beneficiaries

Executive & Congress

International partners

US People

Security

DoD, DHS
Intelligence
Other Gov. Ag. in security roles (DoE)

Exploration

Explorers
Scientists
NASA (exploration related offices)

Educator

K-12
Universities
Other (e.g. museums)

Economic

Commercial
Health providers
Other Gov. Ag. in non-security roles (FAA, HHS, EPA, NOAA)

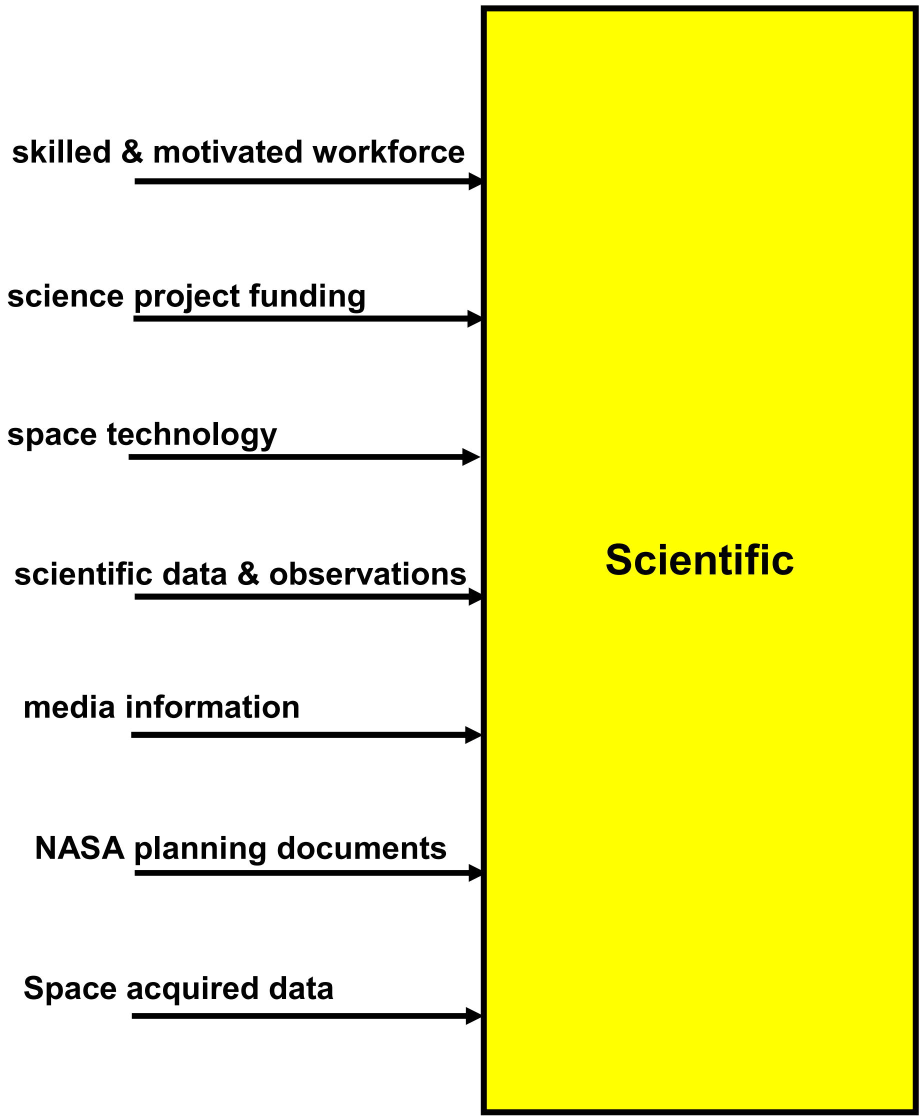
Media

Organized media
Direct delivery media

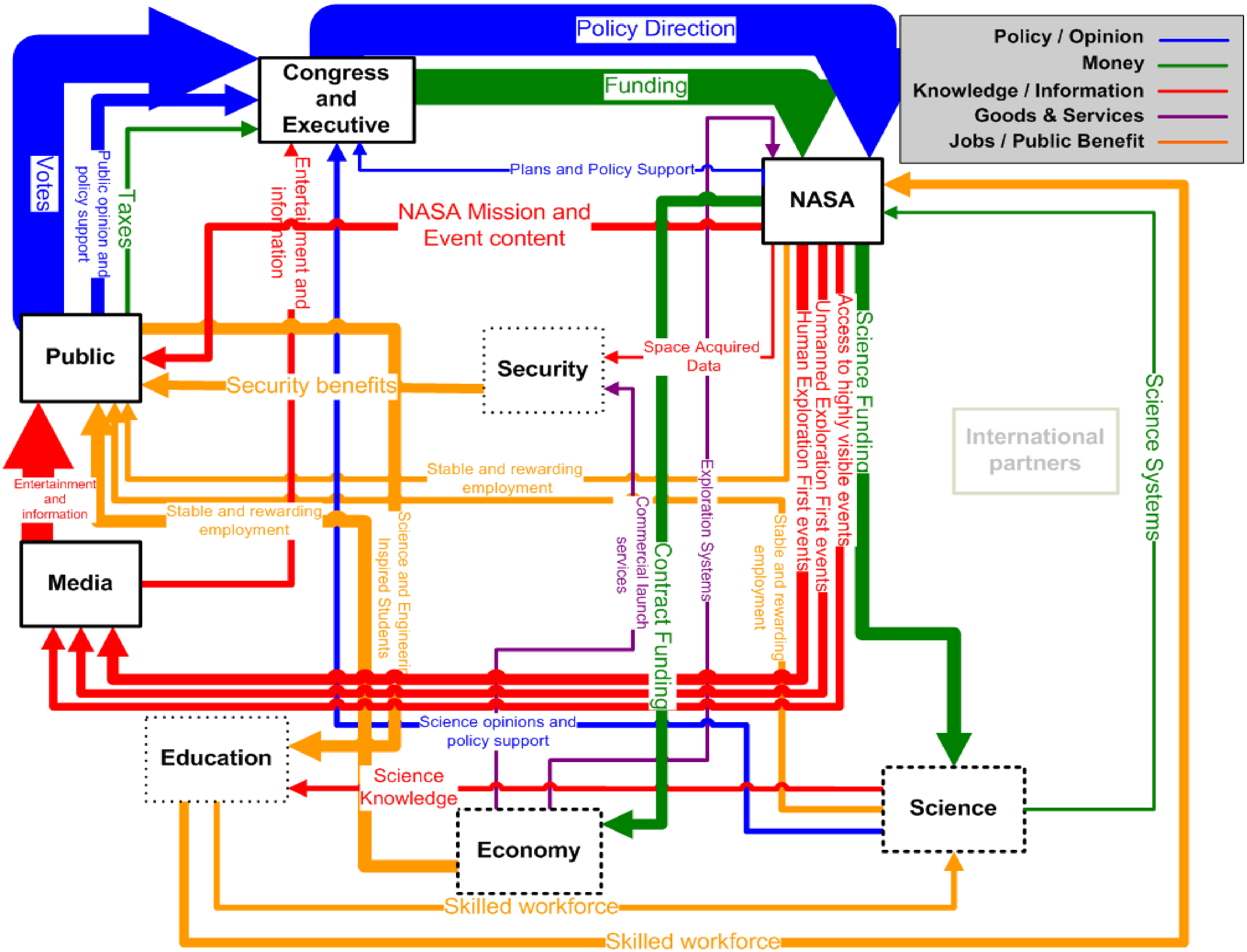
Science

Scientists
Other Gov. Ag. in science roles (NIH)
NASA scientists

Stakeholder Needs - Scientific Community



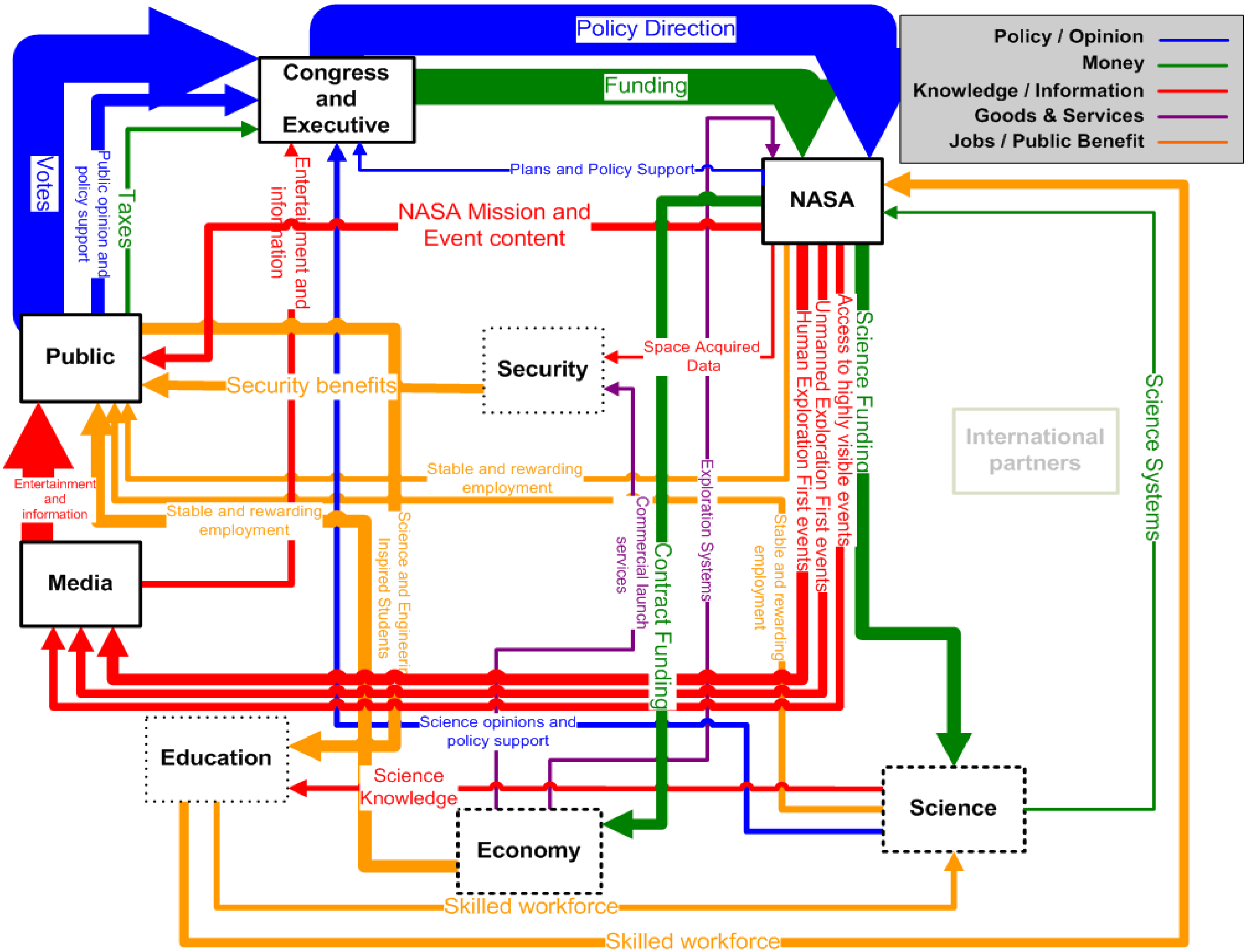
- Identify the needs of stakeholders, and what flows to them to satisfy that need
- Assess the relative importance of the flow to the stakeholder
- Create a network model of the stakeholder community with the project as the central node
- Analyze to gain insight into the delivery of value in the network


Policy / Opinion
Money
Knowledge / Information
Goods & Services
Jobs / Public Benefit
Policy Direction
Funding
Congress and Executive
Votes
Public opinion and policy support
Taxes
Entertainment and information
Plans and Policy Support
NASA
NASA Mission and Event content
Public
Security
Space Acquired Data
Security benefits
Science Funding
Access to highly visible events
Unmanned Exploration First events
Human Exploration First events
Science Systems
International partners
Stable and rewarding employment
Stable and rewarding employment
Entertainment and information
Media
Science and Engineering Inspired Students
Commercial launch services
Contract Funding
Exploration Systems
Stable and rewarding employment
Science opinions and policy support
Education
Science Knowledge
Economy
Science
Skilled workforce
Skilled workforce

Key Findings Stakeholder Model
(not a traditional NASA view)

- Among the most important outputs of NASA Exploration to its stakeholders are:
- Participatory exploration in the form of web and interactive engagement with the public
- A string of human exploration first
- Funding to the scientific community, which supplies instruments, trains students, greats jobs, exerts political influence and of course generates scientific knowledge
- A steady string of unmanned exploration first
- Funding to the commercial community, which supports commercial launch, supplies exploration system, and creates stable and rewarding employment

- On the other hand, status quo could be improved by:
- Better energizing the commercial community to engage, invest, use data, etc.
- Better facilitating the scientific exploration of the moon and solar system
- Better engaging international partners in a strategy that benefits them and NASA
- Engaging the security community, e.g. thought joint development of high value technologies
- Creating specialized materials for educators
- Realizing that there is no real outside stakeholder for "preparation for further exploration," but that this is an internal goal Space technology



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Science Knowledge
Skilled workforce
Skilled workforce

Reflection on Stakeholder Analysis

- Many of the important benefit outputs do relate to campaign design: sequence of events, first, regular progress, etc.
- Some benefit outputs more directly impact the physical/communications system: engage public and media, gather data important to scientific and commercial interests
- Most of the benefit outputs do not relate directly to the design of the CEV, Ares, or the lunar landing, power, habitation - these "infrastructure" and supporting element enable, but mostly show up in affordability and risk measures

Direct Value Delivery

Supporting Systems

"Infrastructure" Systems

What "business" should NASA be in, should it run the apps or or the operating system?
What business should business be in?

Complete Set of Figures of Merit (FOMs)

- FOMs are used to guide architecture selection, and those that measure benefit should be traceable to stakeholder needs.
- In addition to these benefit delivery FOMs, a complete set would include metrics for:
  - Affordability and developmental risk
  - Safety and operational risk
  - Political robustness - will the support be there in the future?
- The choice of FOMs should always be solution-neutral
  - Like well written requirements, FOMs should evaluate solutions, not specify them
- This is an important topic, since you get the answer you set up the FOMs to measure!

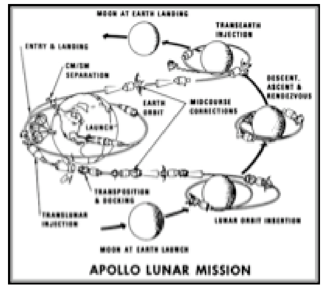
Principle 1: Focus on the Delivery of Value

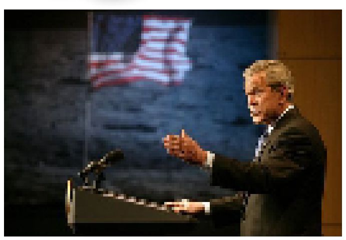
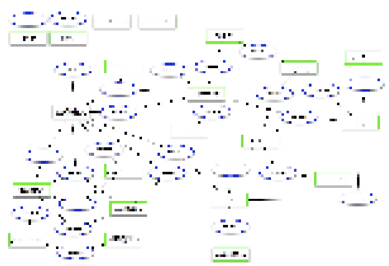
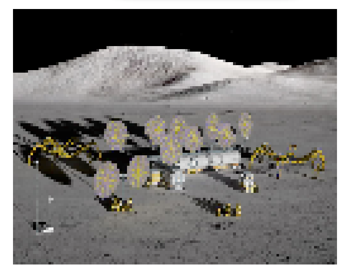
- The focus of the system architecting process should be on delivering value to the stakeholders
  - Stakeholders, their needs and the flow of value have been identified
  - The ways to engage key stakeholders is fairly clear, but not aligned with NASA’s traditional strengths
- The choice of Figures of Merit should be solution-neutral and value-oriented
  - Should reflect benefit, as well as risk, cost and policy robustness
- Work going forward:
  - Validate the stakeholder network analytics
  - Relate working FOMs with high level value delivery (with Cx)
  - Converge on an integrated set of LSS FOMs (with Cx)

Principle 2: Comprehensively Search the Architecture Space to find Good Designs

Decision-Based Analysis

- **System Architects transform a set of needs and goals into a architecture for a system**
  - **They do this by *making decisions***

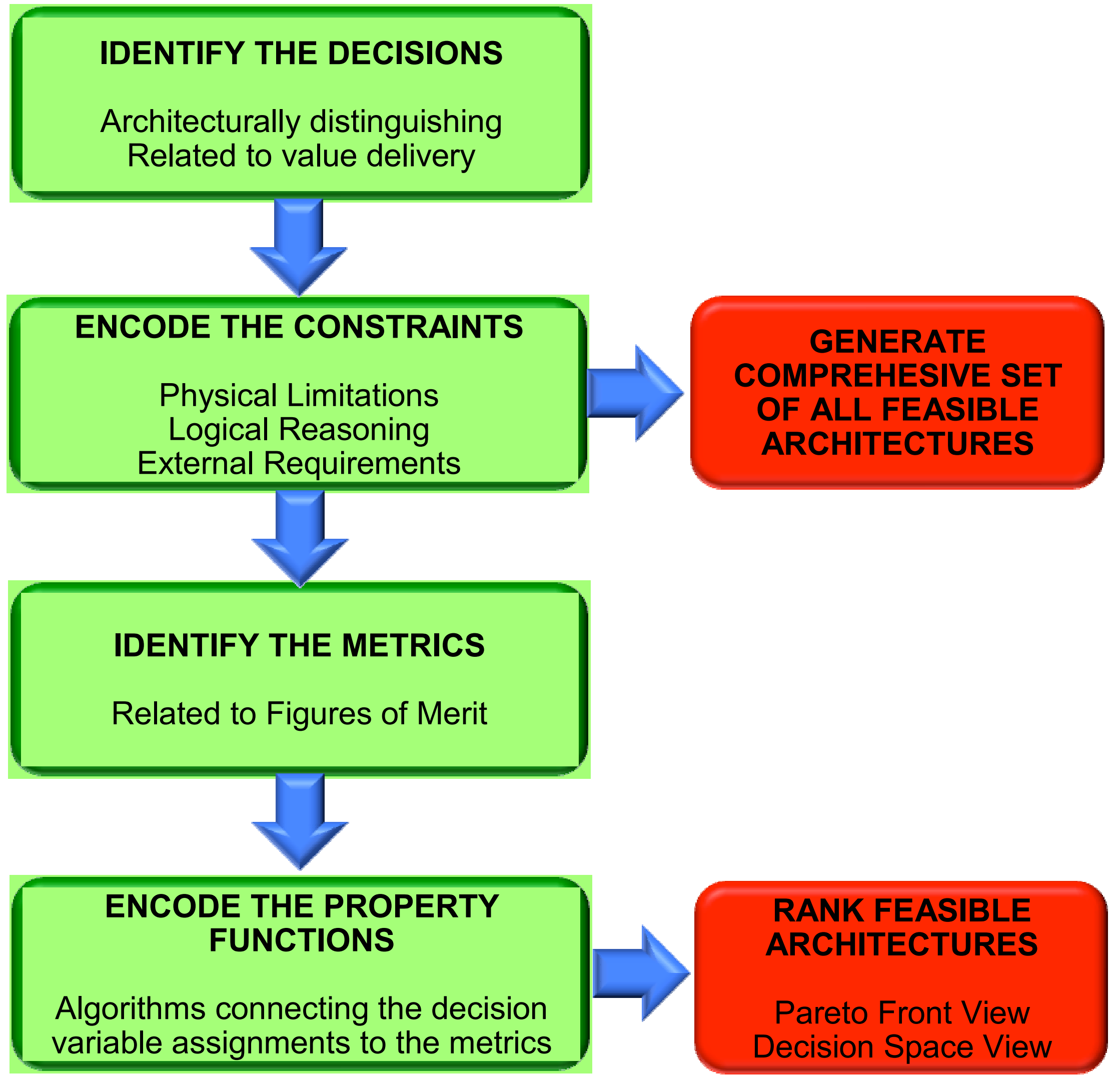



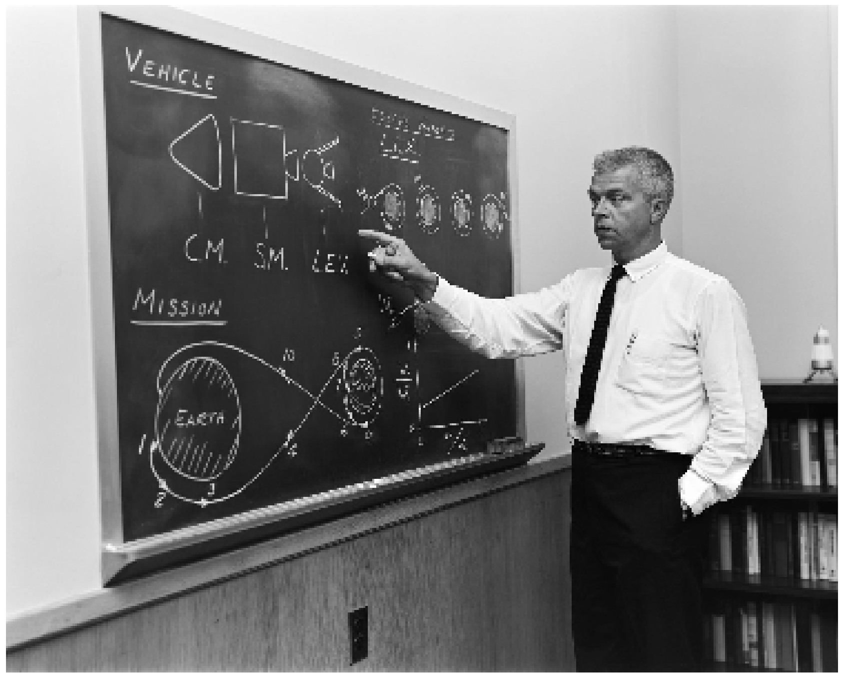
- **An architecture can be represented as a set of decisions and by doing so, the architect can gain useful insight into the space of feasible architectures**

The Architecture Decision Graph Method

- Architecture Decision Graph (ADG) represents an architecture space as a graph connecting:
  - A set of Decision Variables:
    - Represent architectural decisions with a finite set of mutually exclusive alternatives
  - A set of Logical Constraints:
    - Represents propositional statements which restrict the feasible combinations of alternatives for two or more decision variables
  - A set of Property Variables:
    - Represents system properties (metrics) calculated by a property function.
  - A set of Property Functions:
    - Represents the algorithms for calculating system properties that dependant on the decision variable



A Brief Example:
The Apollo Transportation Systems

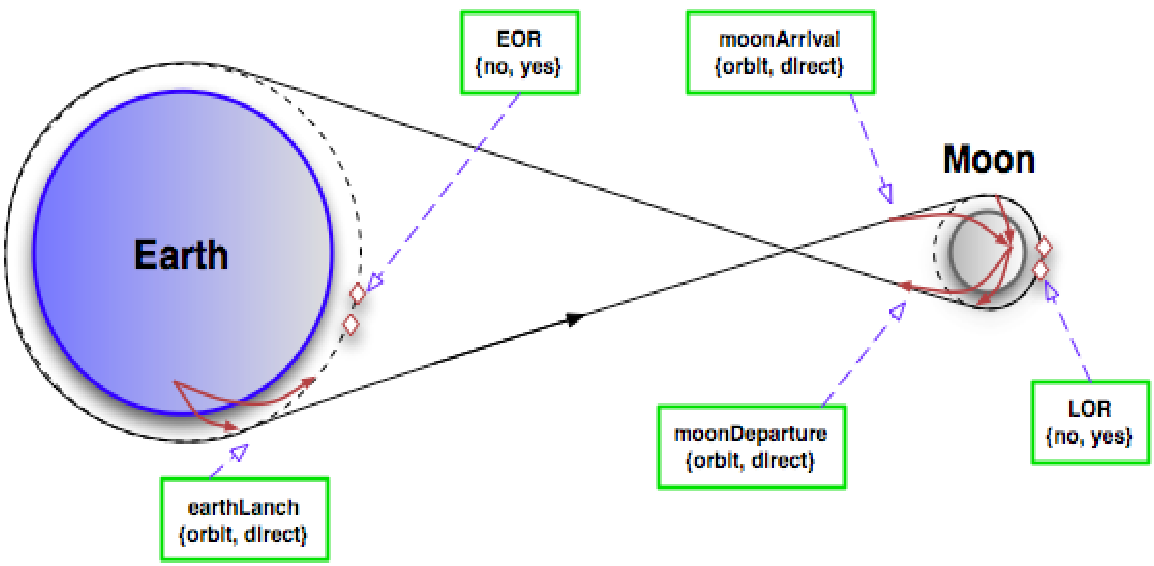


[Source:NASA]

How many architectures: 1? 2? 3? Many?

1. Identifying the Decisions

- **Mission mode related:**

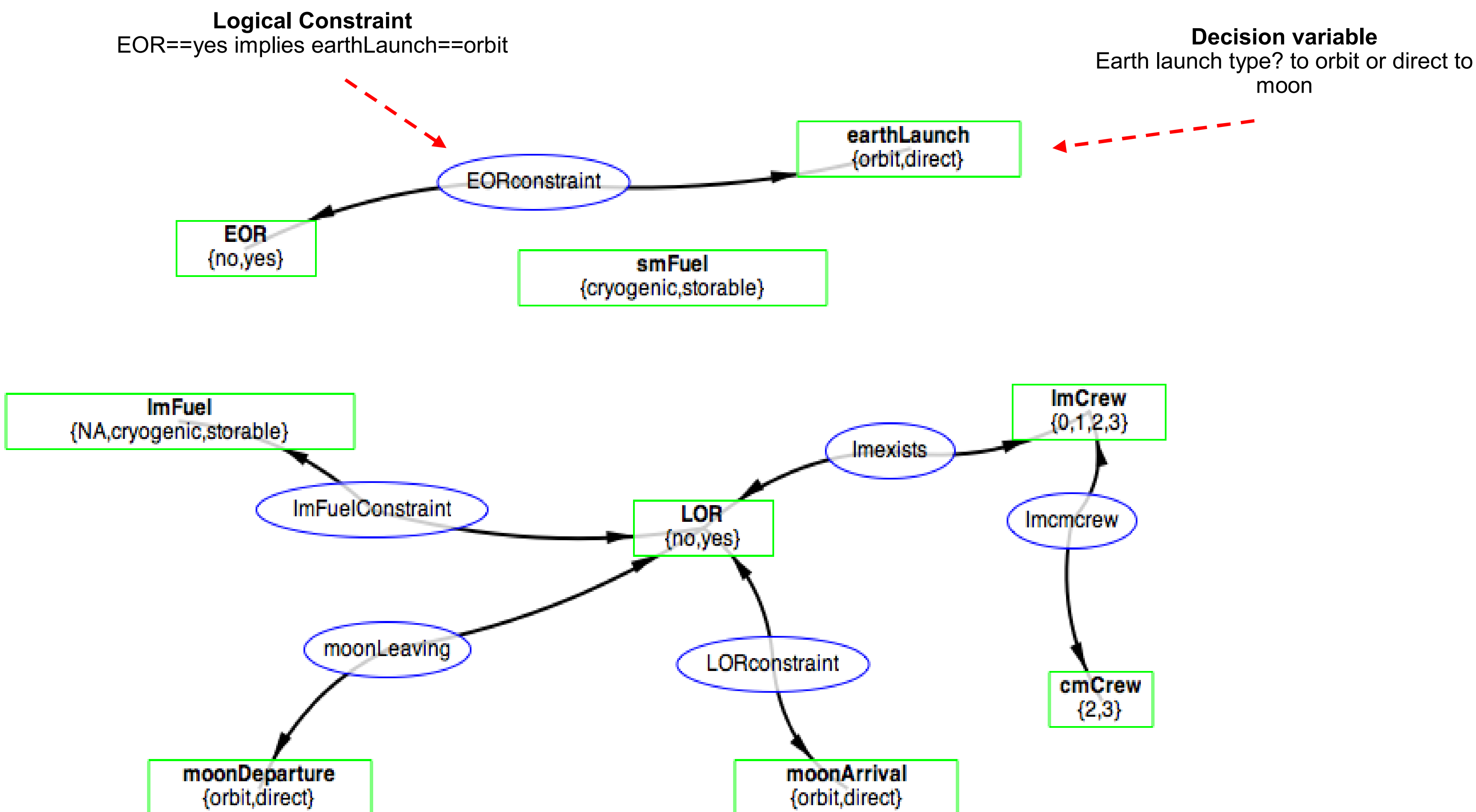


- **Crew size related:**
  - **Command Module Crew: 2 or 3?**
  - **Lunar Module Crew: N/A, 1, 2 or 3?**
- **Fuel/propulsion type related:**
  - **Service module fuel: cryogenic or storable?**
  - **Lunar module fuel: N/A, cryogenic or storable?**

- The three major categories of mission modes are captured by this abstract model: Direct, EOR, and LOR.

9 Decisions !

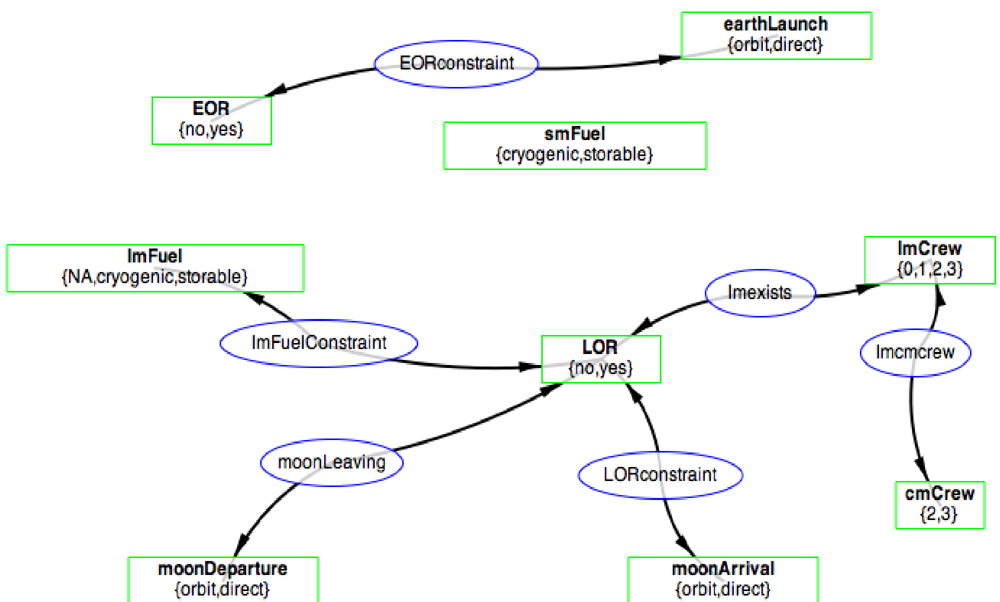
2. Encoding the Constraints



1536 Unconstrained Architectures !

Structural Reasoning

- **Information about the decision variables can be extracted from the structure of the problem itself.**

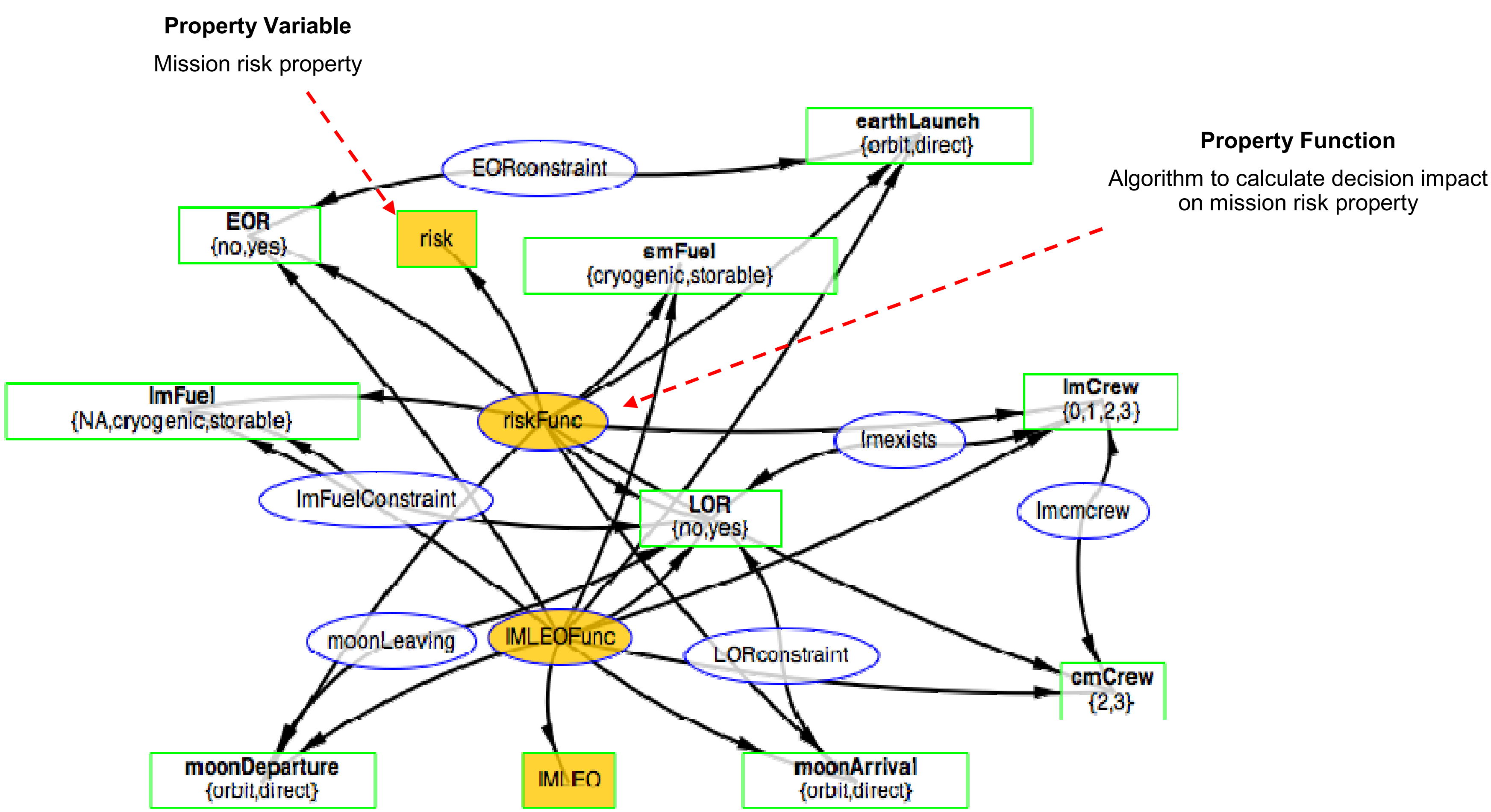


- Example: degree of connectivity

decision	degree
LOR	4
lmCrew	2
cmCrew	1
moonArrival	1
earthLaunch	1
moonDeparture	1
EOR	1
lmFuel	1
smFuel	0

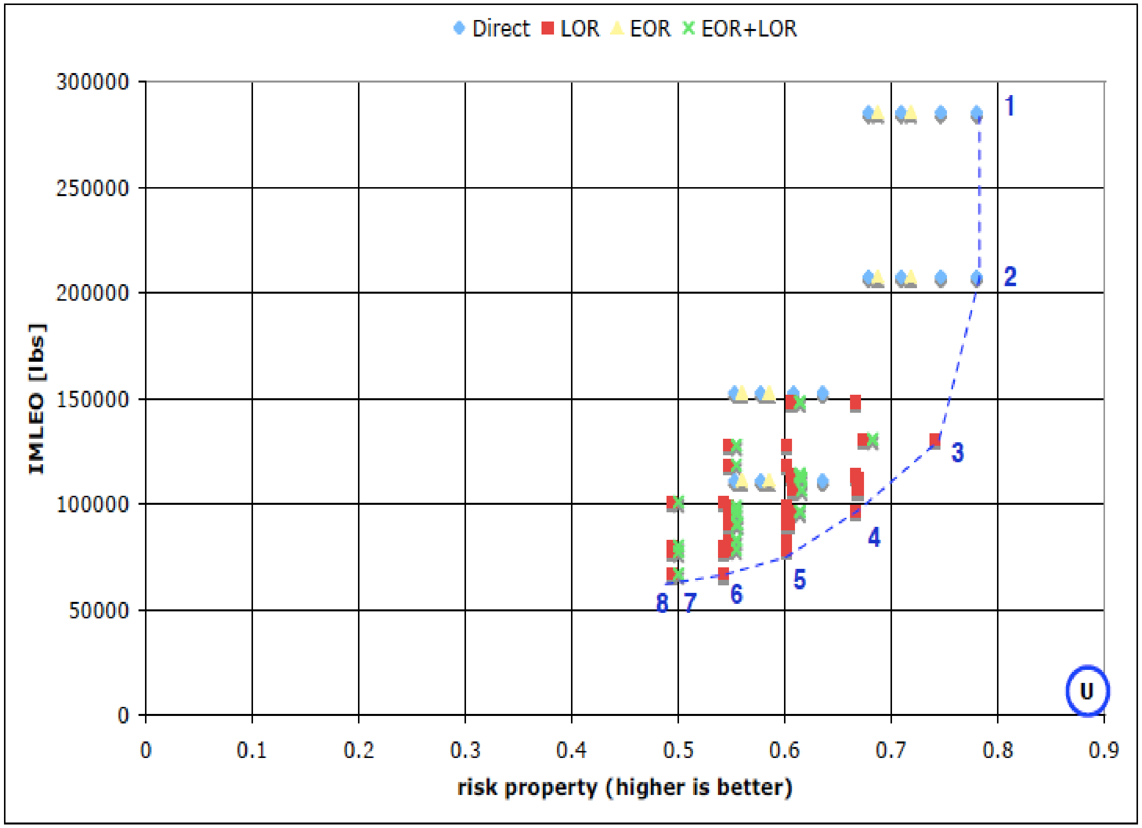
138 Feasible Architectures !

3/4. Encode Property Variables and Functions



Pareto Front of Feasible Solutions

- **IMLEO vs. mission success probability**



Prob of mission success

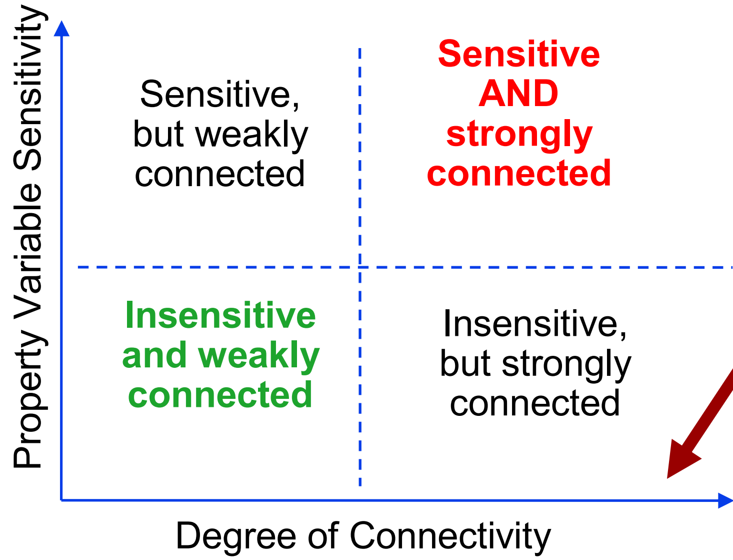
Points on the Pareto front:

- **Point 1: <u>von Braun-like</u>: Direct Mission, with 3 crew, storable propellants**
- **Point 2: Direct with 2 crew, storable propellants**
- **Points 3, 4, 5, 6: LOR missions.**
- **Point 3 is <u>Apollo-like</u>: LOR mission, storable propellants, 3 crew, 2 to surface**
- **Point 7: EOR mission, 2 crew with cryogenic propellants**
- **Point 8: <u>Soviet-like:</u> min mass configuration, LOR, 2 crew, 1 to surface,.**

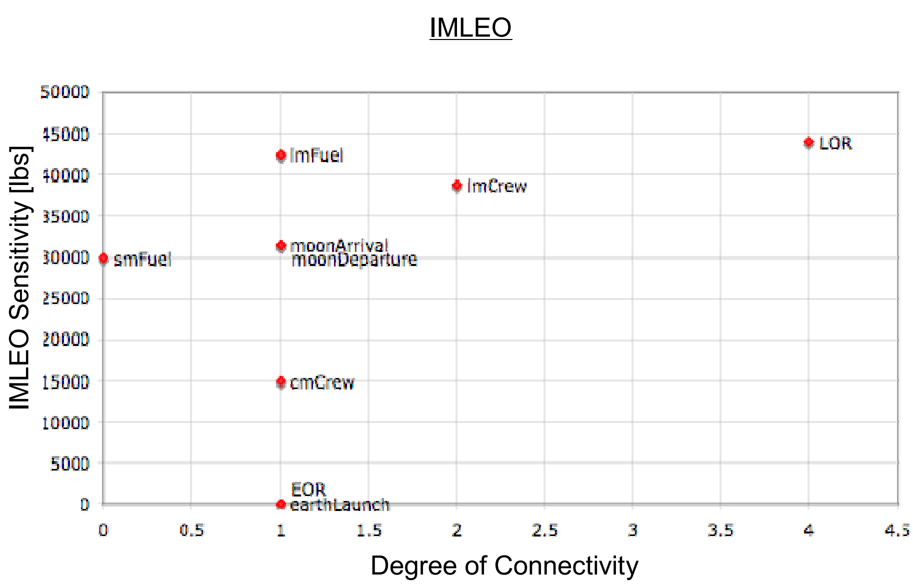
About 3 Good Architectures

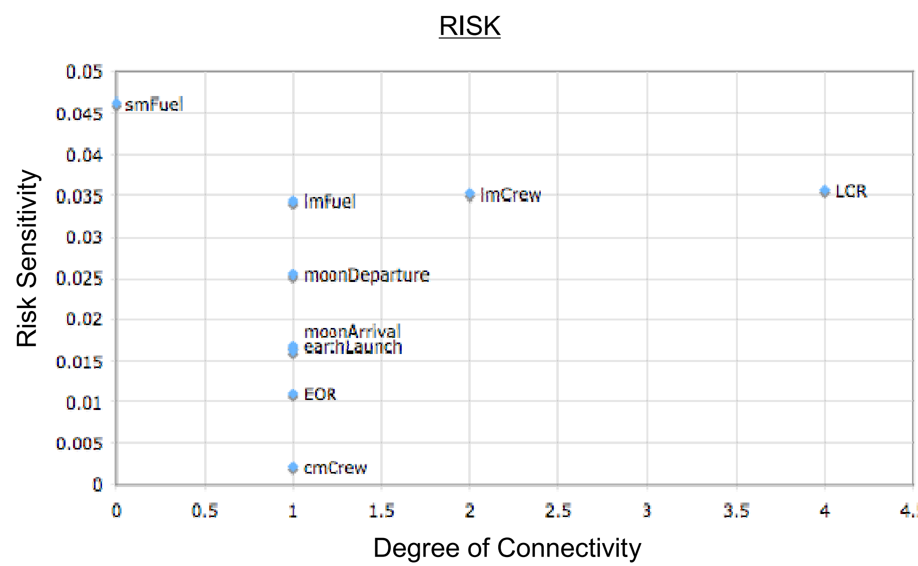
Decision Space Connectivity - Sensitivity View

Sensitivity for property m_j to change in decision d_k



Connectivity for decision d_k





Applying the
Architecture Decision Graph Framework
to the
Lunar Surface System

1. Identifying the Decisions

- The decisions for the LSS are found in the decisions related to the six top-level functions of the system

- Habitation
  - Are habitat modules included?
  - Are multiple habitat modules included?
  - Do the habitat modules need to be transported?
  - Are the habitat modules assembled?
  - Do the habitat modules require ground level access?
  - Do the habitats need to be offloaded from the lander?
- Mobility
  - Can the habitat modules go on long-range excursions?
  - Are pressurized crew cabs included?
  - Are mobility elements included?
  - What type (mass capability) of mobility elements are included?
- Power
  - Is outpost power generation included?
  - What type of power generation for the outpost?
  - Is energy storage used for the outpost?
  - Is mobile power generation included?
  - What type of power generation for mobility?
  - Is energy storage used for mobile?
  - Can stationary power generation be used for mobility?
  - Can mobile power generation be used for the outpost?
  - Can mobile energy storage be used for the outpost?
- Communications
  - What bandwidth is required?
  - How large is the real-time coverage area?
- Logistics
  - Are pressurized logistics containers included?
  - Which design is used for the pressurized logistics containers?
  - Do the logistics containers need to be transported?
  - Do the logistics containers need to be assembled?
  - Do the logistics containers need to be offloaded?
  - Is ISRU used to provide consumables?
- Construction
  - Include an offloading element?
  - What is the offloading capability required?

About 29 Decisions
In conventional System Engineering would treat as a dozen or so trades

The Decisions of the LSS

shortID	Decision	units	alt A	alt B	alt C	alt D	alt E
include_habitat_modules	Are habitation modules included?	none	no	yes			
multiple_habitat_modules	Are multiple habitation modules included?	none	no	yes			
transport_habitat_modules	Do the habitation modules need to be transported?	none	no	yes			
assemble_habitat_modules	Are the habitation modules assembled?	none	no	yes			
ground_level_habitat_modules	Do the habitation modules need ground level access?	none	no	yes			
offload_habitat_modules	Are the habitation modules offloaded?	none	no	yes			
mobile_habitat_modules	Can the habitation modules go on long-range excursions?	none	no	yes			
include_pcc	Are pressurized crew cabs included?	none	no	yes			
include_mobility_elements	Are mobility elements included?	none	no	yes			
mobility_element_type	What type (mass capability) of mobility elements are included?	none	na	small	large	both	
include_outpost_power_gen	Is outpost power generation included?	none	no	yes			
outpost_power_gen_type	What type of outpost power generation is included?	none	na	PV	RTG	PV+RTG	Fission
include_outpost_energy_storage	Is outpost energy storage included?	none	no	yes			
include_mobile_power_gen	Is mobile power generation included?	none	no	yes			
mobile_power_gen_type	What type of mobile power generation is included?	none	na	PV	RTG	PV+RTG	
include_mobile_energy_storage	Is mobile energy storage included?	none	no	yes			
outpost_power_gen_for_mobility	Use the outpost power generation for mobile assets?	none	no	yes			
mobile_power_gen_for_outpost	Use mobile power generation for the outpost?	none	no	yes			
mobile_energy_storage_for_outpost	Use mobile energy storage for the outpost?	none	no	yes			
communications_datatype	What type of data of the communication system have to support?	none	telemetry	HDTV	interactive		
realtime_coverage_area	What is the size of the realtime coverage area?	none	lineOfSight	roverBaseComm			
include_press_logistics_container	Are pressurized logistics containers included?	none	no	yes			
press_logistics_container_design	Choice of design for the pressurized logistics container?	none	na	airlock	PCC	habitat	unique
transport_logistics	Do the logistics containers need to be transported?	none	no	yes			
assemble_logistics	Are the logistics containers assembled?	none	no	yes			
offload_logistics	Are the logistics containers offloaded?	none	no	yes			
ISRU_for_consumables	Is ISRU used to provide consumables?	none	no	yes			
include_offloading_element	Are elements for offloading included?	none	no	yes			
offloading_capability	What capability is required for offloading?	mt	0	less than 6	more than 6		

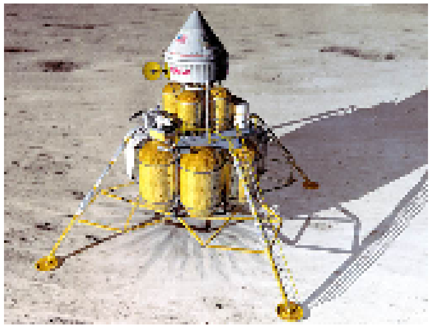
- **To ensure that the choice of 29 decisions was accurate and encompassing, we mapped all available architectures to this matrix.**
- **Each architecture available can be mapped to a distinct space on the matrix.**

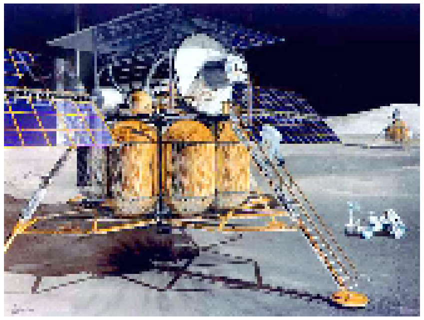
About 30,000,000,000 Unconstrained Architectures !

NASA First Lunar Outpost (1992)

shortID	alt A	alt B	alt C	alt D	alt E
include_habitat_modules	no	yes			
multiple_habitat_modules	no	yes			
transport_habitat_modules	no	yes			
assemble_habitat_modules	no	yes			
ground_level_habitat_modules	no	yes			
offload_habitat_modules	no	yes			
mobile_habitat_modules	no	yes			
include_pcc	no	yes			
include_mobility_elements	no	yes			
mobility_element_type	na	small	large	both	
include_outpost_power_gen	no	yes			
outpost_power_gen_type	na	PV	RTG	PV+RTG	Fission
include_outpost_energy_storage	no	yes			
include_mobile_power_gen	no	yes			
mobile_power_gen_type	na	PV	RTG	PV+RTG	
include_mobile_energy_storage	no	yes			
outpost_power_gen_for_mobility	no	yes			
mobile_power_gen_for_outpost	no	yes			
mobile_energy_storage_for_outpost	no	yes			
communications_datatype	telemetry	HDTV	interactive		
realtime_coverage_area	lineOfSight	roverBaseComm			
include_press_logistics_container	no	yes			
press_logistics_container_design	na	airlock	PCC	habitat	unique
transport_logistics	no	yes			
assemble_logistics	no	yes			
offload_logistics	no	yes			
ISRU_for_consumables	no	yes			
include_offloading_element	no	yes			
offloading_capability	0	less than 6	more than 6		

- Developed a long-duration (45 day) habitat
  - Remained on the lander
  - Did not require resupply
- Transportation architecture used a direct return mission mode





Notional ESAS Outpost (Nov. 2005)

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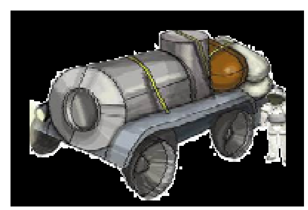
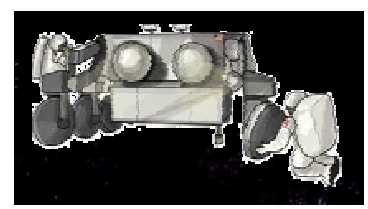
include_habitat_modules	no	yes			
multiple_habitat_modules	no	yes			
transport_habitat_modules	no	yes			
assemble_habitat_modules	no	yes			
ground_level_habitat_modules	no	yes			
offload_habitat_modules	no	yes			
mobile_habitat_modules	no	yes			
include_pcc	no	yes			
include_mobility_elements	no	yes			
mobility_element_type	na	small	large	both	
include_outpost_power_gen	no	yes			
outpost_power_gen_type	na	PV	RTG	PV+RTG	Fission
include_outpost_energy_storage	no	yes			
include_mobile_power_gen	no	yes			
mobile_power_gen_type	na	PV	RTG	PV+RTG	
include_mobile_energy_storage	no	yes			
outpost_power_gen_for_mobility	no	yes			
mobile_power_gen_for_outpost	no	yes			
mobile_energy_storage_for_outpost	no	yes			
communications_datatype	telemetry	HDTV	interactive		
realtime_coverage_area	lineOfSight	roverBaseComm			
include_press_logistics_container	no	yes			
press_logistics_container_design	na	airlock	PCC	habitat	unique
transport_logistics	no	yes			
assemble_logistics	no	yes			
offload_logistics	no	yes			
ISRU_for_consumables	no	yes			
include_offloading_element	no	yes			
offloading_capability	no	less than 6	more than 6		

- 130-day long duration missions
- Single integrated habitat
  - Not offloaded
- Power: nuclear
- Mobility: unpressurized
- Logistics: large containers transported and assembled to habitat



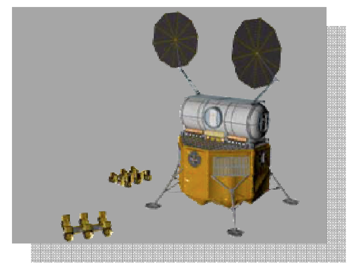


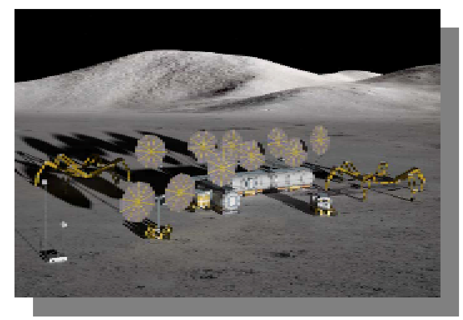
Constellation Architecture Team – LS3 (Phase 2)

Trade

shortID	alt A	alt B	alt C	alt D	alt E
include_habitat_modules	no	yes			
multiple_habitat_modules	no	yes			
transport_habitat_modules	no	yes			
assemble_habitat_modules	no	yes			
ground_level_habitat_modules	no	yes			
offload_habitat_modules	no	yes			
mobile_habitat_modules	no	yes			
include_pcc	no	yes			
include_mobility_elements	no	yes			
mobility_element_type	na	small	large	both	
include_outpost_power_gen	no	yes			
outpost_power_gen_type	na	PV	RTG	PV+RTG	Fission
include_outpost_energy_storage	no	yes			
include_mobile_power_gen	no	yes			
mobile_power_gen_type	na	PV	RTG	PV+RTG	
include_mobile_energy_storage	no	yes			
outpost_gen_for_mobility	no	yes			
mobile_power_gen_for_outpost	no	yes			
mobile_energy_storage_for_outpost	no	yes			
communications_datatype	telemetry	HDTV	interactive		
realtime_coverage_area	lineOfSight	roverBaseComm			
include_press_logistics_container	no	yes			
press_logistics_container_design	na	airlock	PCC	habitat	unique
transport_logistics	no	yes			
assemble_logistics	no	yes			
offload_logistics	no	yes			
ISRU_for_consumables	no	yes			
include_offloading_element	no	yes			
offloading_capability	no	less than 6	more than 6		

- **CxAT examined how to phase the deployment of the outpost elements**
  - **LS3 focused on initial habitation emphasis for phase one**
- **Phase two creates the same “complete” architecture as LS1**



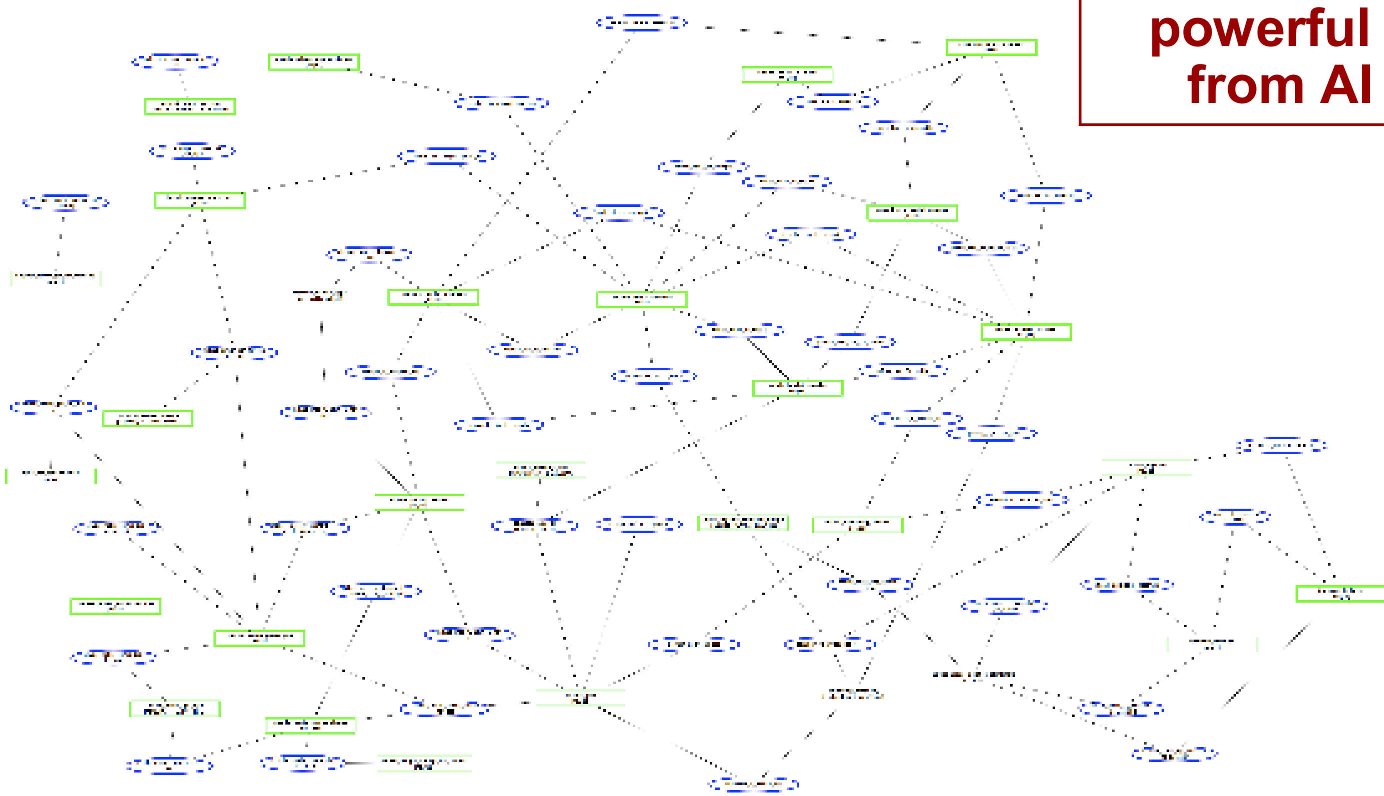


Current LSS treats as dozen or so of such scenarios

Encoding the Logical Connections for the LSS

- The decisions of the Lunar Surface System are constrained based on:
  - Physical limitations of the system
  - Logical reasoning about the system
  - External Constraints

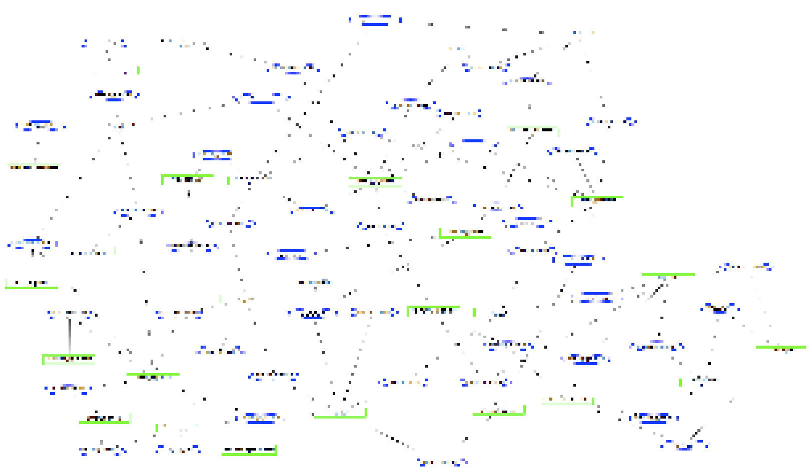
Now in a form for powerful new solvers from AI and CSP's



About 1,500,000 Feasible Architectures !

Structural Reasoning

- **Information about the decision variables can be extracted from the structure of the problem itself.**
  - **Most highly connected decision is whether to include habitation modules**
    - **The decision on the number of habitation modules was not highly connected**
  - **Second most connected decision is whether to offload the habitation modules**
  - **The other highly connected decisions relate to mobility architecture**



decision	degree
include_habitat_modules	8
offload_habitat_modules	7
include_mobile_power_gen	6
include_pcc	6
transport_habitat_modules	6
mobile_habitat_modules	5
include_mobility_elements	5
include_outpost_power_gen	5

Conventional trades are coupled !

The Effects of Outpost Assembly

shortID	Decision	units	alt A	alt B	alt C	alt D	alt E
include_habitat_modules	Are habitation modules included?	none	no	yes			
multiple_habitat_modules	Are multiple habitation modules included?	none	no	yes			
transport_habitat_modules	Do the habitation modules need to be transported?	none	no	yes			
assemble_habitat_modules	Are the habitation modules assembled?	none	no	yes			
ground_level_habitat_modules	Do the habitation modules need ground level access?	none	no	yes			
offload_habitat_modules	Are the habitation modules offloaded?	none	no	yes			
mobile_habitat_modules	Can the habitation modules go on long-range excursions?	none	no	yes			
include_pcc	Are pressurized crew cabs included?	none	no	yes			
include_mobility_elements	Are mobility elements included?	none	no	yes			
mobility_element_type	What type (mass capability) of mobility elements are included?	none	na	small	large	both	
include_outpost_power_gen	Is outpost power generation included?	none	no	yes			
outpost_power_gen_type	What type of outpost power generation is included?	none	na	PV	RTG	PV+RTG	Fission
include_outpost_energy_storage	Is outpost energy storage included?	none	no	yes			
include_mobile_power_gen	Is mobile power generation included?	none	no	yes			
mobile_power_gen_type	What type of mobile power generation is included?	none	na	PV	RTG	PV+RTG	
include_mobile_energy_storage	Is mobile energy storage included?	none	no	yes			
outpost_power_gen_for_mobility	Use the outpost power generation for mobile assets?	none	no	yes			
mobile_power_gen_for_outpost	Use mobile power generation for the outpost?	none	no	yes			
mobile_energy_storage_for_outpost	Use mobile energy storage for the outpost?	none	no	yes			
communications_datatype	What type of data of the communication system have to support?	none	telemetry	HDTV	interactive		
realtime_coverage_area	What is the size of the realtime coverage area?	none	lineOfSight	roverBaseComm			
include_press_logistics_container	Are pressurized logistics containers included?	none	no	yes			
press_logistics_container_design	Choice of design for the pressurized logistics container?	none	na	airlock	PCC	habitat	unique
transport_logistics	Do the logistics containers need to be transported?	none	no	yes			
assemble_logistics	Are the logistics containers assembled?	none	no	yes			
offload_logistics	Are the logistics containers offloaded?	none	no	yes			
ISRU_for_consumables	Is ISRU used to provide consumables?	none	no	yes			
include_offloading_element	Are elements for offloading included?	none	no	yes			
offloading_capability	What capability is required for offloading?	mt	0	less than 6	more than 6		

- **The decisions related to assembly of an outpost can lead to numerous feasible architectures.**
- **The decisions affect not just assembly, but also offloading and transportation.**

15 Inter-related Decisions

The Effects of Outpost Assembly

shortID	Decision	units	alt A	alt B	alt C	alt D	alt E
include_habitat_modules	Are habitation modules included?	none	no	yes			
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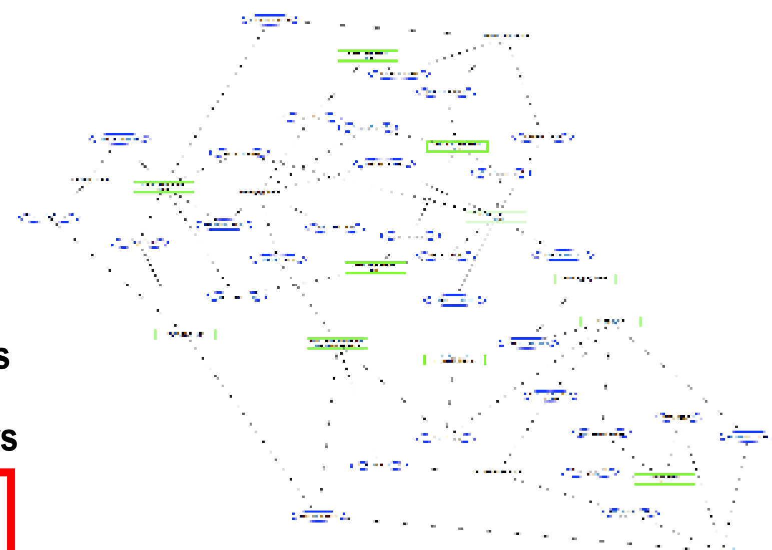
include_offloading_element	Are elements for offloading included?	none	no	yes			
offloading_capability	What capability is required for offloading?	mt	0	less than 6	more than 6		

- **Decisions related to assembly:**
  - **Do we assemble habitats together?**
    - **Requires the capability to offload habitats**
    - **Requires the capability to transport habitats**
  - **Do we assemble logistics containers to habitats?**
    - **Requires the capability to offload habitats and logistics containers**
    - **Requires the capability to transport logistics containers**



- **Decisions related to assembly will size the offloading and transportation capabilities**

The Choice of Power System Architectures

shortID	Decision	units	alt A	alt B	alt C	alt D	alt E
include_habitat_modules	Are habitation modules included?	none	no	yes			
multiple_habitat_modules	Are multiple habitation modules included?	none	no	yes			
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ISRU_for_consumables	Is ISRU used to provide consumables?	none	no	yes			
include_offloading_element	Are elements for offloading included?	none	no	yes			
offloading_capability	What capability is required for offloading?	mt	0	less than 6	more than 6		

- **The decisions related to the power system architecture affect both the cost and performance of the system**

9 Inter-related Decisions

Providing Power to Stationary Assets

shortID	Decision	units	alt A	alt B	alt C	alt D	alt E
include_outpost_power_gen	Is outpost power generation included?	none	no	yes			
outpost_power_gen_type	What type of outpost power generation is included?	none	na	PV	RTG	PV+RTG	Fission
include_outpost_energy_storage	Is outpost energy storage included?	none	no	yes			
include_mobile_power_gen	Is mobile power generation included?	none	no	yes			
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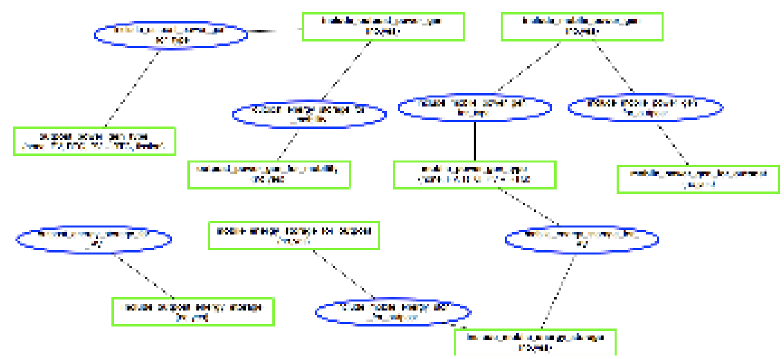
include_mobile_energy_storage	Is mobile energy storage included?	none	no	yes			
outpost_power_gen_for_mobility	Use the outpost power generation for mobile assets?	none	no	yes			
mobile_power_gen_for_outpost	Use mobile power generation for the outpost?	none	no	yes			
mobile_energy_storage_for_outpost	Use mobile energy storage for the outpost?	none	no	yes			

- **Decisions related to choice of power system architecture:**
  - **Type of stationary power generation**
  - **Type of stationary energy storage**
  - **Type of mobile power generation**
  - **Type of mobile energy storage**
- **There are also decisions related to the multi-functionality of elements**
  - **Using mobile power generation to supplement the outpost**
  - **Using mobile energy storage to supplement the outpost**
  - **Using stationary power generation to charge mobile elements**



- **Multi-functionality allows the required capabilities of the elements to be decreased**

Principle 2: Comprehensively Search the Architecture Space to find Good Designs

- Concisely representing the problem as a set of decisions is key to enabling a comprehensive architectural analysis of incredibly large possible spaces
  - The LSS is comprised of decisions related to the six major functions of the system (habitation, mobility, power, communications, logistics, construction)
- The decision representation can allow insight into the critical architectural decisions and their connectivity
  - E.g. architectures that require assembly can require more capable offloading and transportation elements
- Work going forward:
  - Create new concepts to expand space of options
  - Develop value functions consistent with program FOM's, and evaluate
  - Identify central decisions, clusters, and sensitivities

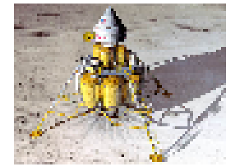
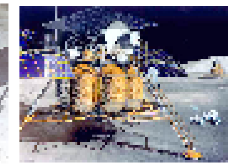
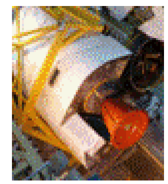
Principle 3: Adopt an Affordable Approach: Minimalist, Commonality, and Extensibility

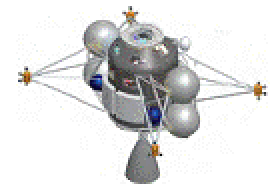
An Affordable Approach to Exploration: Overview

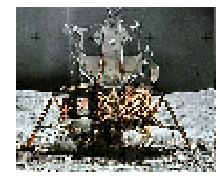
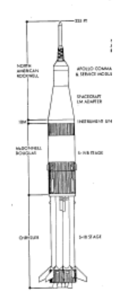
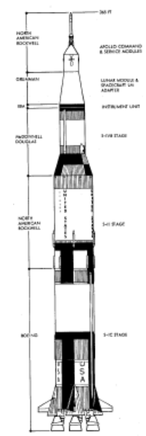
- The approach is aimed at developing a set of initial lunar exploration systems which…
  - Are affordable within the budget and have low developmental risk
  - Provide significant value delivery with regard to key program objectives (e.g. Mars exploration preparation, science, public engagement) early on
  - Lay the foundation for future exploration
- The approach includes
  - Building only the minimum functionality necessary for value delivery
  - Developing commonality at the subsystem level where technically and economically feasible
  - Identifying forward common or extensible elements where economically indicated, and managing the development projects to deliver the economic and risk reduction benefit
- We must decide over what system-life cycle we are trying to reduce cost!

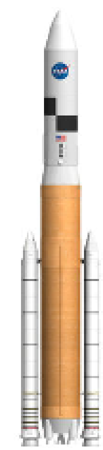
Affordability in NASA Systems: Past and Present

- **Minimalist programs / concepts:**
  - Skylab space station
  - NASA First Lunar Outpost (FLO)
- **Commonality and extensibility:**
  - Extensibility of shuttle OMS to Orion SM and Altair ascent stage
  - Common J-2X engine on Ares I and Ares V upper stages
  - Extensibility of shuttle SRB technology to Ares I and Ares V
  - Common guidance computer for Apollo CSM and LM (MIT Instrumentation Lab)
  - Common S-IVB upper stage on the Saturn IB and Saturn V launch vehicles
  - Common J-2 engine on Saturn V second and third stages

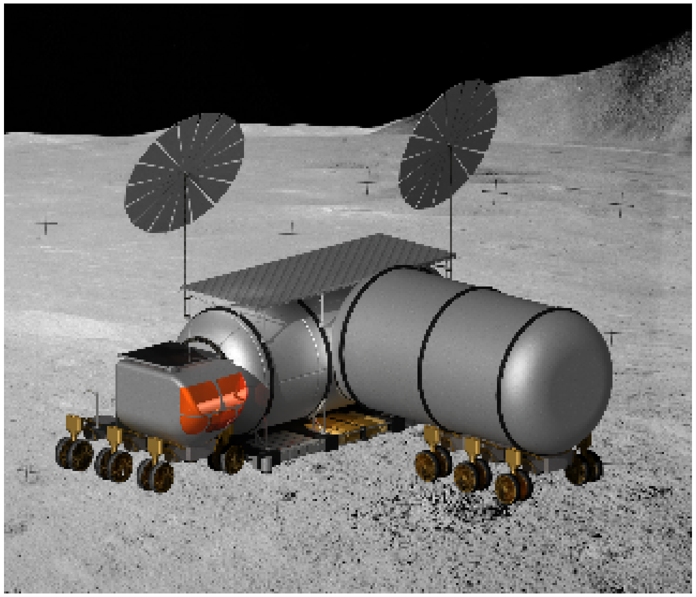




A Minimalist Approach to Lunar Exploration

- Set of initial exploration systems:
  - Transportation system including lander (minimized ascent stage)
  - Pressurized surface mobility system for multi-day traverses
  - Integrated habitat (with power, thermal control, etc.), delivered on a single cargo flight, including high-closure life support system
  - Optional inflatable add-on module, transportable with mobility system



- Provides significant early return in terms of exploration preparation, lunar science, and public engagement for limited (and affordable) initial investment
- Provides a programmatically robust lunar outpost infrastructure (a destination to return to) while preserving programmatic flexibility for US human spaceflight
- Utilizes a Mars-extensible surface architecture for habitation and surface mobility
- Defers development of the infrastructure for continuous presence, providing opportunities for significant (but non-critical) contributions by partners
- Leaves resources for development of future exploration systems

Method for Identifying Technical Commonality

- **We have developed a methodology for systematically identifying commonality opportunities which are technically feasible and economically beneficial**
  - **This is a necessary, but not sufficient condition for effective commonality**
  - **Managerial and organizational feasibility is assessed separately**
- **The architecture-level methodology is based on the following four steps:**

Step 1: requirements analysis for systems considered → **Step 2:** point design architecture analysis (no commonality) → **Step 3:** screening of point designs for commonality opportunities → **Step 4:** evaluation of commonality benefit

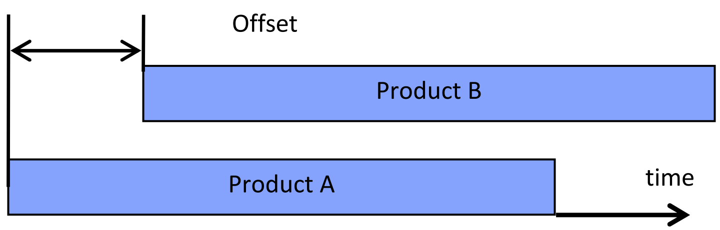
- **The methodology has been applied to a number of case studies, including:**
  - **In-space propulsion systems for human Moon / Mars missions**
  - **Life support systems for human exploration**
  - **Lunar and Mars surface power systems**
  - **Lunar and Mars surface mobility systems**
  - **Lunar and Mars surface habitats and associated structures / pressure vessels**

Specific Technical Commonality Opportunities

- Opportunities for commonality and extensibility in life support:
  - Re-use of the CEV carbon dioxide and humidity removal system design for the Altair lunar lander ascent stage and for the lunar pressurized rover
  - Use of a common carbon dioxide and humidity removal system for future long-duration exploration habitats based on ISS subsystem design
  - Use of a common water regeneration system for future long-duration exploration habitats based on ISS subsystem design
  - Use of a common food system with predominantly de-hydrated food for future long-duration exploration habitats
- Opportunities for commonality and extensibility in surface power:
  - Use of a common high-density energy storage technology on the lunar and Mars surface: advanced Li-Ion batteries and / or regenerative fuel cells
  - Use of Stirling RTG units for mobile and stationary applications on the Moon and Mars; could be based on or extend technology currently being developed by SMD
  - Option for using commercial thin-film solar array technology on the surface of Mars
- Use of a common integrated habitat unit on the Moon and Mars, possibly with a common inflatable module which is attached to the habitat on the surface

Management and Economics of Commonality

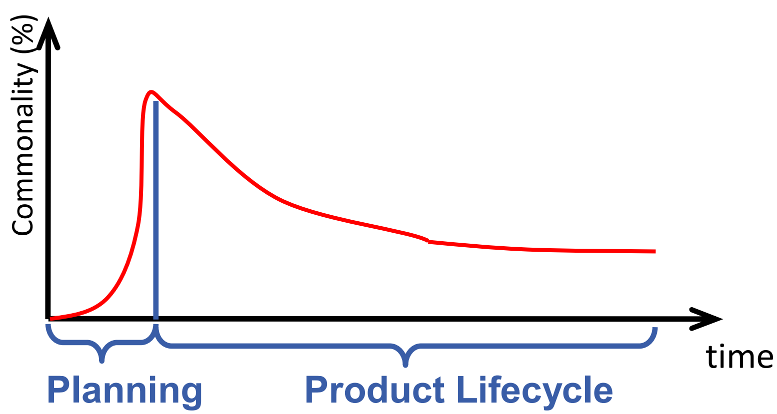
- In order to develop a general and useful approach to the management and economic evaluation of commonality, we studied 7 case studies of product families, 4 in aerospace and 3 outside
- The literature and scholarship on commonality dominantly deals with project is a *family started at the same time*
- The first important observation is that in nearly all cases, *sequential development* occurs
- Sequential development happens because of:
  - Market factors: testing market with first variant, or different dates of need
  - Technology factors: technology capability development; and learning from earlier products
  - Organizational factors: organizational focus on a product, and human resource constraints
  - Financial factors: total program cost, and cash flow management, budgetary restrictions



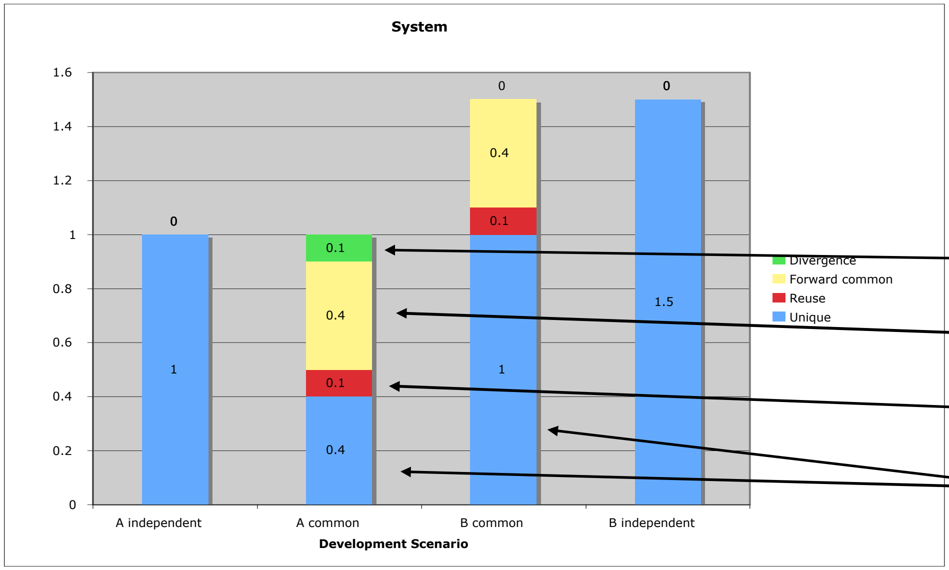
In reality, commonality often occurs sequentially and becomes extensibility

Trends in the Evolution of Commonality

- What happens in sequential development
  - Easier to promise commonality than to deliver
    - What looks common at a high level is difficult to deliver as one examines more detailed views
  - Planned commonality diverges over time
    - Due to acceptable factors: market change, technology, learning
    - Due to less acceptable factors: poor managing, intentional pursuit of uniqueness, failure to consider lifecycle benefits
  - Time offsets reduce the potential benefits of commonality
  - Time offsets shift the potential benefits to later variants and incur the cost in the earlier benefits
  - Later variants of larger volume derive less benefit than later variants of smaller volume
  - Commonality must be actively managed to stick



Commonality Economic Model



- Content of two project A and B
  - Divergence
  - Successful forward common
  - Reuse
  - Unique to A or B
- Non-recurring costs:
  - Penalty for development of forward common in A
  - Penalty for integration of successful forward common and reuse into B
- Recurring costs
  - Learning (improved reliability)
  - Economies of scale
  - Penalty for excess capability in A and B

Insights from the Economic Model

- For all forms of commonality recurring benefits of commonality to A decrease with increasing offset
  - Higher divergence in non-recurring
  - Less economy of shared production in recurring

- Reuse is always a win to B, and should be carefully considered in any design before commitment to to new development

- Forward commonality usually provides net benefit to the family of A+B, but almost always incurs additional cost for A
  - Should consider a new metric - return on commonality investment R
  - R = (total incremental savings in A + B)/(incremental cost in A)

Case Studies Identify Effective Practice in the Management of Commonality

- Approaches to Managing Commonality
  - Careful reuse of existing components
  - Intentionally common building block development
    - Develop one or a few common high value or large expense components that all variants will use
  - More distributed development of intentionally common elements
    - Planning process that addresses divergence and offset through sensitivity analysis
    - Tracking and labeling of common in PDM system
    - Formal organizational structure to manage commonality
    - Decision process that consider benefit across the family
  - Create a culture of assessing commonality benefit

Principle 3: Adopt an Affordable Approach: Minimalist, Commonality, and Extensibility

- Investment into a limited set of minimal exploration system elements which are extensible to later program phases
  - Minimalist delivery of core functionality that delivers value
  - Identify is technically feasible within lunar system
  - Identify where forward commonality to Mars is feasible
- Explicit consideration of life-cycle costing, and management planning for commonality within the lunar exploration system and between the lunar exploration system and future exploration systems
- Work going forward:
  - Final report of technical options for commonality
  - Examine commonality in two Cx systems, e.g. pressure suits
  - Adapt the economic and management model to NASA environment

Presentation Summary: Three Principles of Architecting

- **Focus on the Delivery of Value**
  - The focus of the system architecting process should be on delivering value to the stakeholders
  - The choice of Figures of Merit should be solution-neutral and value-oriented

- **Comprehensively Search the Architecture Space to find Good Designs**
  - Concisely representing the problem is key to enabling a comprehensive architectural analysis of incredibly large possible spaces
  - The decision representation can allow insight into the critical architectural decisions and their connectivity

- **Adopt an Affordable Approach: Minimalist, Commonality, and Extensibility**
  - Investment into a limited set of minimal exploration system elements which are extensible to later program phases
  - Explicit consideration of life-cycle costing, and management planning for commonality within the lunar exploration system and between the lunar exploration system and future exploration systems